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Chemical Composition of Pen Surface Layers of Beef Cattle Feedyards[1]

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ABSTRACT

The biological, physical, and chemical characteristics of beef cattle feedyard pen surfaces may affect nutrient transformations and losses to the atmosphere, ground water, or surface water. Feedyard pen surfaces can typically segregate into 3 or 4 layers. The purpose of this study was to determine if there were seasonal, within-pen location, days-on-feed, or urine effects on the chemical composition of the pen surface layers of feedyards. Samples were collected from 5 locations in 9 pens at 3 feedyards in each season and were analyzed for gravimetric water, pH, electrical conductivity (EC), nitrate + nitrite-N (NO_x-N), ammonia + ammonium-N (NH_x-N), N, C, and P. The percentage of water increased ($P < 0.01$) with depth among the manure layers and decreased in the soil. The pH of the manure layers increased with depth ($P < 0.01$) from approximately 7.6 to 8.2. The EC of the manure layers was greater ($P < 0.01$) than the EC of the soil layer, whereas the NO_x-N concentration was greater ($P < 0.01$) in the soil layer. The NH_x-N concentrations were lowest in the soil layer ($P < 0.01$). Total C and N concentrations decreased ($P < 0.01$) with sample depth. The composition of the layers was affected by season and location within the pen. Recent urine deposition did not affect the lower layers. The NH_x-N concentration of the layers increased with days on feed. The differences in the chemical and physical properties of the layers in a feedlot pen may potentially affect nutrient losses to the atmosphere and to groundwater.

Key words: beef cattle, feedlot, ammonia, nitrate, manure

INTRODUCTION

In beef cattle feedyards, large quantities of nutrients are applied to the pen surface in feces and urine. Significant quantities of excreted N may volatilize from the pen surface as ammonia (NH_3-N) or nitrous oxide (N_2O) or may be lost to surface or ground water through runoff and percolation (Morse, 1996; US EPA, 2001, 2003). These losses of reactive N decrease the fertilizer value of the manure and can potentially have adverse effects on the environment (Galloway et al., 2003).

Decomposition of pen surface manure occurs by both physical and microbial processes. The accumulation of manure, the hoof action of cattle, microbial activity in the manure, and environmental factors cause physical and biochemical changes that result in the formation of distinct layers in the feedlot pen surface. Mielke et al. (1974) reported that 3 layers developed on a feedlot pen surface: 1) a layer of loose manure, 2) an interface layer of mixed manure and soil, and 3) the underlying soil. The physical and chemical characteristics of these layers may potentially affect N transformations, N distribution, and N losses to the environment (Mielke et al., 1974; Buresh and Patrick, 1978; Mikkelsen et al., 1995; Stevens et al., 1998; Miller and Berry, 2005; Uchida et al., 2008).

Data are limited on N transformations that occur in the pen surface of feedlots. Increased knowledge of the physical and chemical factors in feedlot pen surfaces would be useful in understanding factors that contribute to NH_3-N and N_2O volatilization and nitrate leaching potential from feedyards. To that end, the objectives of this study were to 1) characterize differences in the chemistry of the layers normally encountered in feedyard pen surfaces, 2) determine the effects of pen location and season on the

[1] Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.
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chemistry in the layers, 3) determine the effects of length of feeding on the chemistry of the layers, and 4) determine the effects of recent urine deposition on the chemistry of the layers.

MATERIALS AND METHODS

Study Sites

Pen surface samples were collected from 3 open-lot commercial beef cattle feedyards (A, B, and C) located in the Southern High Plains of Texas. Below each feedyard was a Pullman clay loam soil (fine, mixed, superactive, thermic Torretic Paleustoll; Geiger et al., 1968; Jacquot et al., 1970; Mitchell et al., 1974) that had a loamy surface layer and firm clay subsoil. Concrete pads approximately 3 m wide were located around all water troughs and behind the feed bunks. In each feedyard, cattle were normally fed for 115 to 200 d and pens were cleaned of accumulated manure 2 or 3 times per year, whenever the cattle in that pen went to slaughter. Typical starting weights ranged from 250 to 300 kg and typical finishing weights ranged from 550 to 700 kg. Pens ranged in size from 630 to 4,200 m^2 and contained 40 to 300 animals. The typical stocking density was approximately 15 m^2/head. At all 3 yards, the high-concentrate finishing diets fed were typical of the Southern Great Plains (Vasconcelos and Galyean, 2007). Diets were based on steam-flaked corn and contained 7 to 10% alfalfa hay and 13 to 14.5% CP (DM basis).

Feedyard A contained approximately 20,000 cattle and sloped to the west, where the solids in runoff were removed using settling basins and the runoff was collected in a man-made retention pond. Pens in feedyard A had no mounds and had water troughs located between the pens. The manure removed from the pens was immediately taken off site and applied to farm land. Feedyard B contained approximately 30,000 cattle and sloped to the west, where the solids in the runoff were removed using settling basins and the runoff was collected in a natural playa that served as the retention pond. Pens in feedyard B contained no mounds and the manure removed from pens was stockpiled on site. The water troughs in feedyard B were located between or in the middle of the pens. Feedyard C contained approximately 45,000 cattle and sloped to the east, where solids in the runoff were removed using settling basins and the runoff was collected in a natural playa. Feedyard C had water troughs located between the pens. Pens in feedyard C contained mounds composed primarily of aged manure, which covered 50 to 75% of the pen area. Most manure was stockpiled as mounds (1 to 3 m high) in the pens, and a portion of the manure was composted in windrows on site.

Weather data were collected at each yard by using an electronic weather station (Unidata America, Lake Oswego, OR) and 2-min averages. Soil temperature probes were set up outside cattle pens at depths of 51 and 152 mm, and a tipping bucket rain gauge was set at a height of 1 m. Data were collected for the minimum, maximum, and average air and soil temperature and precipitation. Meteorological data were stored using a Starlogger data logger (Model 6004B 128K, Unidata America) and downloaded every 14 d.

Sample Collection

Nine pens at each feedyard were initially selected in April based on the approximate number of days the cattle had been in the pen. At each yard, 3 pens were randomly selected in which cattle had been on feed a short time (<45 d), 3 pens were randomly selected in which cattle had been on feed an intermediate length of time (45 to 100 d), and 3 pens were randomly selected in which cattle had been on feed a long period of time (>100 d). Within each pen, 5 sample locations were selected and sampled once during each season (spring, summer, fall, and winter). Stratified (by area of the pen) judgmental sampling was used to select 2 sample locations at the front of the pens, 2 at the back of the pens, and 1 from the middle of the pen for feedyards A and B. Feedyard C sample locations included the northeast corner, middle-east side, southeast corner, front of the mound, and back of the mound. Sampling on the east side of the pen allowed for comparison of samples obtained near (within 3 m) the water trough and away from the water trough. On 40 occasions, judgmental sampling within the 5 sample locations was also used to collect samples from wet areas that had recent (<30 min) urine deposition for comparison with other samples within the same pen.

During preliminary investigations at the same feedyards as in the present study, we noted that the surface of pens at each feedyard generally developed into 4, rather than 3 (Mielke et al., 1974), distinct layers. Therefore, samples were collected from these 4 layers. A loose, unconsolidated layer of manure accumulated on the pen surface as a result of cattle hoof action (designated "loose"). Below this layer, a densely compacted dry manure layer developed (designated "dry-pack"). A wetter, more compacted, manure layer formed below the dry layer (designated "wet-pack"; Figure 1). With the exception of the mound area, the last sampled layer below the pen was the soil layer (designated "soil"). The depth of the layers from the loose surface to the soil layer varied from 25 to 304 mm. The loose samples were obtained by carefully scraping manure from an area of approximately 0.5 m^2 with a garden trowel. Samples from the dry-pack, wet-pack, and soil layers were then obtained from the same area by digging a shallow trench approximately 300 to 400 mm deep and 10 cm wide with a pickax. Layers were separated by hand based on color and texture, placed into individually labeled Whirl-Pak bags, and frozen until laboratory analyses were performed. Observations were made at each sample collection and included the following: time of day, approximate days cattle had been on feed, estimated average BW of cattle in the pen, cattle genetics (British-cross, Brahman-cross, etc.), pen slope (front or back), pen size, approximate number of cattle in the pen, sex (heifer or steer), and pen location in the feedyard.

Laboratory Analyses

Pen surface samples were ground with a cutting mill (Retsch Grindomix 200, Retsch GmbH and Co., Haan, Germany) and analyzed as wet samples. Gravimetric water content was determined by drying to a constant weight at 100°C for 24 h. Organic matter content was determined by ashing samples in a muffle furnace at 550°C overnight. To determine pH and electrical conductivity (**EC**), approximately 5 g (DM basis) of undried sample was mixed with 25 mL of deionized water for 20 min. The pH was determined with a glass electrode and pH meter (Corning 125, Science Products, Medfield, MA) by a modification of the procedure of Peech (1965). Electrical conductivity was determined using a modification of the procedure of the US Environmental Protection Agency (method 9050A; US EPA, 1996) using a glass electrode and EC meter (Accumet 30, Fisher Scientific, Hampton, NH). Nitrate + nitrite-N (**NO_x-N**), and ammonia + ammonium-N (**NH_x-N**) were determined in a 2:20 (wt/vol) extract of sample DM and 2 *M* KCl (US EPA, 1983b). Approximately 5 g of DM was mixed with 50 mL of 2 *M* KCl. After being shaken for 30 min, the samples were filtered through Whatman 42 filter paper and the filtrates were analyzed for NO_x-N and NH_x-N concentrations with a flow injection analyzer (Lachat ASX 8000, Hach Co., Loveland, CO). The NO_x-N concentrations were determined with a cadmium-copper reduction column according to QuikChem method 12-107-04-1-B (Knepal, 2001) derived from US EPA (1983b) method 353.2. The NH_x-N concentrations were determined according to QuikChem method 10-107-06-1-J (Smith, 2001) derived from US EPA (1983a) method 350.1. After wet digestion, total P was determined colorimetrically with

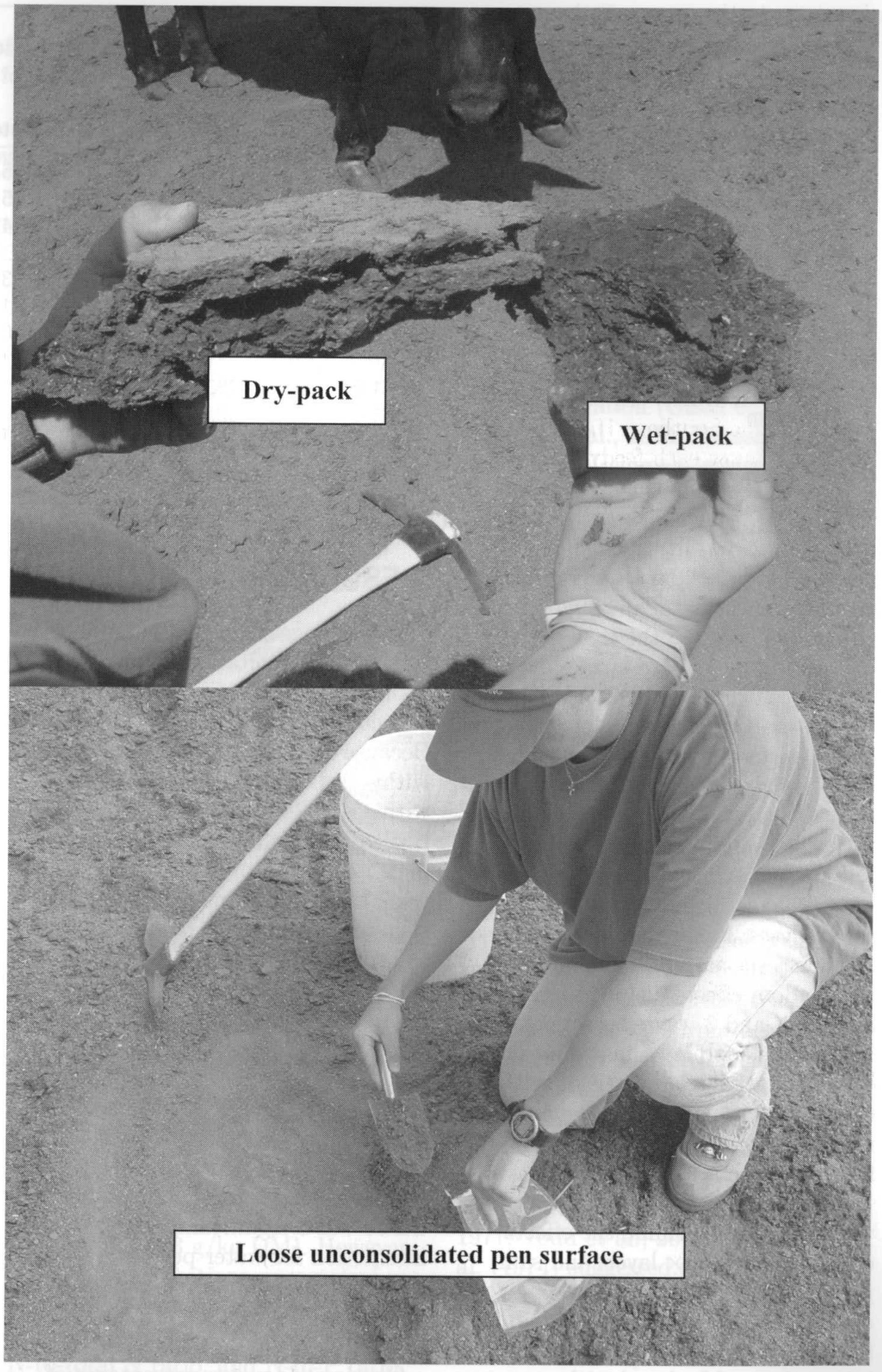

Figure 1. Sampling of loose unconsolidated pen surface (bottom photo) and the underlying dry hard-pack and wet hard-pack (top photo) layers of the feedlot pen surface.

the flow injection analyzer (Lachat method 15-115-01-4A; AOAC, 1990). Total C and N were determined by combustion in a C-N analyzer (Elementar Vario MAX CN, Elementar Americas Inc., Mt. Laurel, NJ).

Statistical Analyses

Statistical analysis was performed (SAS Institute, 1999) using the MIXED procedure. When a significant *F*-test was obtained, differences in treatment least squares means were

Table 1. Average weather data at feedyards A, B, and C during the 2 wk immediately before sampling (mean ± SD)

Item	April (Spring)	July (Summer)	October (Fall)	December (Winter)
Minimum temperature, °C	3.9 ± 5.0	19.2 ± 1.9	5.9 ± 3.6	−3.4 ± 3.0
Maximum temperature, °C	23.6 ± 4.8	35.5 ± 2.1	25.1 ± 6.6	17.8 ± 4.8
Average temperature, °C	14.1 ± 4.5	27.3 ± 1.8	14.9 ± 4.4	5.6 ± 3.7
50-mm soil temperature, °C				
Minimum	13.3 ± 2.2	26.9 ± 0.7	13.5 ± 2.2	1.3 ± 1.8
Maximum	21.2 ± 2.1	36.3 ± 1.3	21.1 ± 2.9	9.2 ± 2.2
Average	16.9 ± 1.9	31.1 ± 0.7	16.9 ± 2.4	5.0 ± 1.6
150-mm soil temperature, °C				
Minimum	14.4 ± 1.9	28.2 ± 0.5	15.6 ± 1.9	3.5 ± 1.2
Maximum	18.3 ± 1.8	32.8 ± 0.7	19.4 ± 2.2	7.1 ± 1.4
Average	16.3 ± 1.8	30.5 ± 0.4	17.4 ± 2.0	5.3 ± 1.1
Total precipitation, mm	0.19 ± 0.07	0.10 ± 0.03	0.00 ± 0.00	0.00 ± 0.00

determined using the PDIFF procedure. For these data, any significant differences noted in the text are at $P < 0.05$.

Samples from feedyards A, B, and C were used to determine the effects of pen surface layer, days on feed, and the days on feed × layer interaction, and to compare wet urine spots with dry spots in the same pens. This was the only time the wet urine spot samples were included in the statistical analyses. In the analysis of layers, days on feed, and their interaction, the random effects included feedyard and all 2- and 3-way interactions of feedyard with layer and days on feed. In statistical analysis of wet urine spots, random effects included feedyard and the interactions of feedyard with season and urine.

Samples from feedyards A and B were used to determine the effects of season, season × layer, and sampling location (front, middle, or back of pen). Random effects included feedyard and all 2-, 3-, and 4-way interactions of feedyard with season, layer, and location.

Because it was the only feedyard that contained mounds, feedyard C was used for analysis of mound and water trough effects. Random effects included days on feed and the interactions of days on feed with season and mounds.

RESULTS AND DISCUSSION

The average air and soil temperatures and precipitation during the 2 wk immediately before samples were collected are presented in Table 1. Because all feedyards were sampled within 2 d of each other and were within a 100-km radius, the data were pooled for the 3 feedyards. In general, little or no precipitation occurred the week before the pens were sampled; therefore, the pen surfaces were dry at each sampling.

Seasonal and Layer Effects: Feedyards A and B

The water, OM, pH, EC, and total C content of the pen surface layers at feedyards A and B during the 4 seasons are presented in Table 2. There was a significant season × layer interaction for water percentage; however, there was no significant season × layer interaction for pH, EC, OM, or total C.

Gravimetric water percentages of the loose and dry-pack layers were significantly affected by season, with the water percentage being approximately 47% lower in the summer than the winter. The water content of the dry-pack layer was greater than the loose and soil layers and, as expected, the water content of the wet-pack layer was greater than the other 3 layers.

The pH of the loose, dry-pack, and soil layers was significantly affected by season. The pH increased with depth from the loose to dry-pack to wet-pack layer, and then decreased in the soil layer. These results contrast with those of Miller et al. (2003), who noted no effect of season on the pH of manure and bedding collected at a Canadian feedlot, but agree with those of Woodbury et al. (2001) , who noted that pH increased with sample depth. Electrical conductivity was greater in the 3 manure layers than in the soil layer, but was not affected by season. The EC of the loose and dry-pack layers tended ($P < 0.07$) to be greater in fall and winter than in spring and summer. Miller et al. (2003) reported that season did not affect EC of feedlot manure and bedding.

Organic matter content of the loose and dry-pack layers was greater in winter than in the remaining seasons (Table 2). As expected, the OM concentration of the manure layers was greater than that of the soil layer. In agreement with the results of Woodbury et al. (2001), the total C concentration in the manure layers decreased as depth increased (Table 2), which is probably the result of increased mixing of manure with the underlying soil as the depth increased, thus diluting manure C with soil. In addition, in the deeper pen surface layers, there may be greater anaerobic microbial

Table 2. Water, pH, electrical conductivity, OM, and total C content (DM basis) of pen surface samples from feedyards A and B during each of the 4 seasons

Item and layer	Spring	Summer	Fall	Winter	Mean	SEM[1]
Water,[2] %						
Loose	8.6[a]	6.7[a]	12.8[b]	12.7[b]	—	0.03
Dry-pack	23.3[b]	12.3[a]	19.1[ab]	23.1[b]	—	0.04
Wet-pack	33.5	30.5	29.5	31.8	—	0.05
Soil	13.0	11.1	12.1	11.6	—	0.03
pH						
Loose	7.74[bc]	7.55[a]	7.65[b]	7.87[c]	7.70[x]	0.02
Dry-pack	8.16[b]	7.81[a]	7.85[a]	8.00[ab]	7.94[xy]	0.02
Wet-pack	8.27	8.16	8.11	8.22	8.20[y]	0.03
Soil	8.15[b]	7.91[a]	8.00[ab]	7.92[a]	8.00[xy]	0.03
Electrical conductivity, S/m						
Loose	0.94	1.06	1.22	1.20	1.11[y]	0.14
Dry-pack	0.93	0.99	1.06	1.05	1.02[y]	0.16
Wet-pack	0.96	1.15	0.99	1.14	1.05[y]	0.24
Soil	0.35	0.35	0.36	0.33	0.34[x]	0.07
OM, g/kg						
Loose	615[a]	602[a]	670[ab]	725[b]	646[y]	14.6
Dry-pack	498[a]	537[a]	543[a]	633[b]	550[y]	24.7
Wet-pack	509	527	488	533	523[y]	20.0
Soil	68	96	66	55	71[x]	5.4
C, g/kg						
Loose	296[a]	311[b]	354[c]	370[d]	333[y]	3.3
Dry-pack	258[a]	259[a]	302[b]	318[b]	280[y]	4.2
Wet-pack	239	249	261	284	253[y]	4.8
Soil	34	31	34	24	32[x]	1.9

[a–d]Means within row with different superscripts differ ($P < 0.05$).

[x,y]Means within column and item with different superscripts differ ($P < 0.05$).

[1]Pooled SEM for the overall pen surface layer mean.

[2]Season × layer interaction ($P < 0.05$).

fermentation of manure to CO_2 or methane. As with OM, the total C concentration in the top 2 pen surface layers was greatest in the winter, followed by the fall, summer, and spring. Similarly, Miller et al. (2003) reported that the total C content of feedlot manure and bedding sampled from an Alberta feedlot was 15% greater ($P < 0.001$) in the winter than in the spring and summer. Microbial activity in the pen surface would be expected to be lower during colder months. Thus, C and OM could be lost at a slower rate and could accumulate in the pen surface. McCalla and Elliott (1971) noted that if a feedlot surface maintained an organic layer over the soil surface, pollutants were less likely to leach to the groundwater, and anaerobic conditions were maintained in the underlying soil layer.

The total P concentration in the manure layers (mean 7.9 ± 0.6 g/kg DM) was greater than in the soil layer (mean 0.9 ± 0.3 g/kg DM). However, total P concentrations were not affected by season.

The NO_x-N, NH_x-N, total N, NH_x-N-to-total N ratio, and N-to-P ratio of the pen surfaces in feedyards A and B are presented in Table 3. The mean concentrations of NH_x-N in the loose surface and dry-pack layers were similar, although there tended to be seasonal variation. During the spring and summer, NH_x-N concentrations tended ($P < 0.10$) to be greater in the dry-pack layer than the loose surface, whereas the opposite was true during the fall and winter. The lowest mean NH_x-N concentration occurred in the soil layer and the greatest mean concentration occurred in the wet-pack layer. Similarly, Schuman and McCalla (1975) noted that NH_x-N concentrations were highest on the pen surface and decreased with depth, and that NH_x-N concentrations on the pen surface were 35 times greater than the concentration in an adjacent field. The accumulation of NH_x-N in the wet-pack layer is probably the result of anaerobic conditions that limit nitrification (Olsen et al., 1970; Adriano et al., 1974; Buresh and Patrick, 1978). Using an in vitro system, Stewart (1970) noted that NH_x-N moved downward through the soil column only after the cation exchange capacity of the soil became saturated with ammonium.

The NH_x-N concentrations in the loose layer were 2 times greater in the winter than in the summer (Table 3). Similarly, in Canada, Miller et al. (2003) noted that NH_x-N concentrations in pen surface manure + bedding were 57 to 186% greater in the fall and winter than in the spring and summer. The lower concentrations of NH_x-N noted during the summer and spring may be the result of greater volatilization of NH_3-N from the pen surface during the warmer seasons. Ammonia emissions from urea applications increase with increasing temperature (Ernst and Massey 1960; Burch and Fox, 1989), and NH_3-N emissions from feedyards are approximately 2 times greater in the summer than in the winter (Elliott et al., 1971; Todd et al., 2008). Adriano et al. (1974) suggested that temperature and moisture affect NH_3-N volatilization because of their effects on microbial activity and the evaporation of water.

The NO_x-N concentrations in the pen surface increased as depth increased from the loose to the soil layer. There was not a significant effect of season on the NO_x-N concentrations in the pen surface, although concentrations were numerically greater in spring than in the remaining seasons. In contrast, Miller et al. (2003) reported that the NO_x-N

Table 3. Ammonium + ammonia N (NH_x-N), nitrate + nitrite N (NO_x-N), total N, NH_x-N as a percentage of total N, and N-to-P ratio (DM basis) of pen surface samples from feedyards A and B during each of the 4 seasons

Item and layer	Spring	Summer	Fall	Winter	Mean	SEM[1]
NH_x-N, mg/kg						
Loose	2,001[a]	1,501[a]	2,154[a]	3,200[b]	2,221[y]	62.3
Dry-pack	2,857[b]	1,898[a]	1,765[a]	2,540[b]	2,224[y]	77.5
Wet-pack	3,740	3,602	2,689	3,174	3,188[z]	120.4
Soil	1,769[c]	1,402[b]	1,190[a]	916[a]	1,328[x]	61.3
NO_x-N, mg/kg						
Loose	25.6	10.2	4.5	8.5	12.1[x]	6.2
Dry-pack	36.2	24.1	15.6	14.6	21.3[x]	6.4
Wet-pack	50.6	19.0	19.6	28.6	27.9[x]	10.7
Soil	78.2	83.9	98.3	89.1	87.0[y]	6.2
Total N, g/kg						
Loose	24.2[a]	26.4[a]	28.9[b]	30.7[b]	27.5[y]	0.4
Dry-pack	25.3[ab]	24.8[a]	26.3[bc]	27.3[c]	26.0[y]	0.6
Wet-pack	23.4	23.0	24.3	28.3	25.0[y]	2.0
Soil	4.0	4.7	4.3	4.2	4.3[x]	0.4
NH_x-N:total N, %						
Loose	8.15[b]	5.93[a]	6.54[a]	10.29[c]	8.18[x]	0.25
Dry-pack	13.81[c]	8.02[b]	5.84[a]	8.82[b]	9.04[x]	0.31
Wet-pack	16.92	16.58	13.76	15.70	17.35[y]	0.67
Soil	55.29[b]	36.76[a]	31.15[a]	31.74 [a]	39.51[z]	1.62
N:P ratio						
Loose	3.78[a]	3.66[a]	3.49[a]	4.53[b]	4.27[y]	0.12
Dry-pack	3.79	3.41	3.20	3.97	3.79[x]	0.09
Wet-pack	3.41	3.42	2.88	3.23	3.32[x]	0.08
Soil	6.02	4.92	6.08	5.96	5.81[z]	0.26

[a–c]Means within row with different superscripts differ ($P < 0.05$).

[x–z]Means within column and item with different superscripts differ ($P < 0.05$).

[1]Pooled SEM for the overall pen surface layer mean.

concentrations of pen surface manure + bedding in Canada were 114 to 269% lower in the spring than in the fall, winter, or summer. However, Elliott and McCalla (1972) reported that nitrate concentrations were undetectable in the feedlot surface from December to August. Mielke et al. (1974) reported nitrate concentrations of 50 mg/kg in the top few centimeters of the pen surface, which decreased to less than 2 mg/kg at a depth of 1.8 m. Schuman and McCalla (1975) reported nitrate concentrations that ranged from 7 to 9 mg/kg at 5 cm to less than 1 mg/kg at a 10-cm depth on a feedlot surface. These were less than one-half the concentrations noted in a farmed field.

Concentrations of NO_x-N and NH_x-N in the pen surface layers are dependent on a combination of biological and chemical reactions, such as urea hydrolysis, N mineralization, ammonification, nitrification, denitrification, NH_3-N volatilization, N_2O release, dissimilatory nitrate reduction to NH_3-N, and chemo-denitrification (Stevens and Laughlin, 1998; Stevens et al., 1998). These reactions are, in turn, regulated by chemical and physical characteristics of the pen surface, such as temperature, permeability, moisture, and salinity.

Nitrates in the pen surface manure can subsequently be lost as N_2O, a powerful greenhouse gas, or as innocuous di-N gas via nitrification and denitrification. Nielsen et al. (1996) suggested that a coupled nitrification-denitrification process could occur at a soil-manure interface. Mielke et al. (1974) and Mielke and Mazurak (1976) reported that the interface layer of the feedlot pen surface had a high bulk density and low air permeability, which limited infiltration below the pen surface. Because of the high bulk density and low air and water permeability, the interface layers of the feedyard pens may help maintain conditions favorable for denitrification (Mielke and Mazurak, 1976) and also restrict the movement of nitrates through the pen surface profile (Mielke et al., 1974; Schuman and McCalla, 1975). Biological denitrification requires NO_x-N, organic C, denitrifying bacteria, and anoxic conditions—conditions that exist within a feedlot pen surface. Elliott and McCalla (1972) suggested that nitrification, which requires oxygen, takes place at the feedlot surface and that denitrification, an anaerobic process, takes place beneath the surface. Somewhat in contrast, Woodbury et al. (2001) noted that nitrification activity was greater in the packed manure layer than the loose unconsolidated surface layer and that denitrification activity was greatest in the unconsolidated surface and least in the soil layer. McCalla and Elliott (1971) found high nitrate concentrations in samples taken 30 cm below the feedyard surface, but nitrate concentrations were lower below that depth, suggesting either that denitrification was occurring below the feedlot or that very little N percolated below 30 cm.

The optimal temperature for NO_x formation from NH_x is between 27 and 35°C (Brady and Weil, 2002), similar to the soil temperature during our summer sampling (Table 1). Nitrification is slow when the soil temperature falls below 10°C (Sabey et al., 1956), such as during our winter sampling (Table 1). The reported optimal temperatures for denitrification are similar, ranging from 25 to 35°C (Brady and Weil, 2002) up to 60°C (Bremner and Shaw, 1958). The optimal pH for nitrification is approximately 8.5 (Tisdale et al., 1985), and the optimal moisture content is approximately 60% of available pore space (Brady and Weil, 2002), which are conditions somewhat similar to the wet-pack and soil layers in our study. At a pH of less than 7, the major product released by denitrification is N_2O, whereas at a pH greater than 8, such as in our feedlot wet-pack and soil layers, di-N gas is the primary form of N lost (Wijler and Delwiche, 1954; Tisdale et al., 1985). Nitrification can be slowed by factors such as salt-induced stress and NH_3-N toxicity, leading to increased NH_3-N volatilization (Monaghan and Barraclough, 1992). Denitrification can also be inhibited by high NH_x-N and salt concentrations (Monaghan and Barraclough, 1992; Petersen et al., 2004). In a laboratory-scale system, Miller and Berry (2005) noted no emissions of N_2O or methane from a 75:25 manure-to-soil surface but appreciable emissions from 25:75 and 5:95 manure-to-soil surfaces.

Total N concentrations of the loose layer were significantly greater in the winter and fall than in the summer and spring (Table 3). The greater total N concentrations coincide with greater NH_x-N and total C concentrations during the winter. Again, the greater N concentrations may be the result of the effects of colder temperatures on microbial activity and on volatilization of N and C. In agreement with these results, the proportion of total N in the loose layer that was NH_x-N was also greater in winter than in summer, with spring and fall being intermediate. The proportion of total N present as NH_x-N also increased with sample depth. Because of the lower N concentrations, the N-to-P ratio in the loose layer was affected by season.

The C-to-N ratio of the pen surface was not affected by season but decreased ($P < 0.05$) as depth increased from an average of 12.5 ± 0.3 in the loose layer to 11.3 ± 0.1 in the dry-pack, 10.6 ± 0.1 in the wet-pack, and 8.5 ± 0.2 in the soil layer (data not shown). The C-to-N ratio in all 4 layers during all 4 seasons was always less than 25, which should stimulate net mineralization of N and microbial decomposition of manure OM because N is not limiting for microbial decomposition (Van Faassen and Van Dijk, 1987). Conversely, when the C-to-N ratio is greater than 25 and microbial activity is limited by available N, the conversion of inorganic N ions to organic N in microbial tissue occurs more rapidly (Brady and Weil, 2002), but the rate of decomposition of OM is decreased (Van Kessel et al., 2000).

Table 4. Total N and total C content (DM basis) of the pen surface samples from feedyards A and B taken from the back, middle, and front of each pen

Item and layer	Back	Middle	Front	Mean	SEM[1]
Total N, g/kg					
Loose	26.3^{a}	27.7^{ab}	28.4^{b}	27.5^{y}	1.0
Dry-pack	25.8	25.3	26.5	26.2^{y}	1.5
Wet-pack	23.9	24.4	26.2	24.8^{y}	1.2
Soil	4.4	4.8	3.9	4.4^{x}	0.8
Total C, g/kg					
Loose	325^{a}	315^{a}	352^{b}	330^{y}	11
Dry-pack	275^{a}	265^{a}	310^{b}	281^{y}	8
Wet-pack	256	265	262	247^{y}	17
Soil	34	33	27	31^{x}	11

^{a,b}Means within row with different superscripts differ ($P < 0.05$).

^{x,y}Means within column and item with different superscripts differ ($P < 0.05$).

[1]Pooled SEM for pen surface delayer mean.

Spatial Variation Within the Pen: Feedyards A and B

Because of animal behavior, urine and feces excretion, mound formation, and water spills from water troughs, there is the potential for significant spatial variation in pen surface chemistry. However, in our study the water, NO_x-N, and NH_x-N concentrations, pH, EC, C-to-N ratio, and NH_x-N-to-total N ratio were not affected by location within the pen (data not shown). Ward et al. (1978) also noted that pH was not affected by pen location, whereas Woodbury et al. (2001) noted greater pH at the rear of the pen than at the front (nearest the feed bunk). Woodbury et al. (2001) found that the denitrifying enzyme activity of the unconsolidated surface material (our loose surface) at the front of the pen was lower than at the back or middle of the pen.

The total N concentration of the loose surface was significantly affected by location within the pen, being greater at the front of the pen than at the back of the pen (Table 4). Woodbury et al. (2001) and Ward et al. (1978) also found that the total N concentration in the loose surface layer was greater at the front of the pen than at the middle or back of the pen.

Similarly, total C concentrations of the loose and dry-pack layers were greater near the front of the pen than at the middle or rear of the pen (Table 4). Woodbury et al. (2001) and Ward et al. (1978) noted similar results. These results are probably attributable to cattle spending more time near the feed bunk at the front of the pen and thus excreting more feces and urine than in other pen locations, and thus might be affected by pen stocking density.

Effects of Mounds and Water Troughs: Feedyard C

Total C concentration, EC, NO_x-N concentrations, and C-to-N ratio of pen surface samples were not affected by mound or nonmounded location or by the proximity to a water trough.

Table 5. Water, pH, ammonium + ammonia N (NH_x-N), and total N concentration (DM basis) of pen surface samples from mounded and unmounded areas and from areas near or more than 10 m from water troughs at feedyard C

Item and layer	On mound	Off mound	Mound effect, *P*-value	Near water trough	Away from trough	Water trough effect, *P*-value
Water, %						
Loose	10.1^{x}	13.7^{x}	<0.01	14.1^{x}	10.9^{x}	<0.06
Dry-pack	16.0^{y}	20.3^{y}	<0.01	22.6^{y}	19.0^{y}	<0.01
Wet-pack	32.6^{z}	31.8^{z}	<0.36	35.0^{z}	31.4^{z}	<0.02
Soil	—	10.8^{x}	—	10.8^{x}	11.7^{x}	<0.86
pH						
Loose	7.93^{x}	8.03^{x}	<0.07	7.93^{x}	7.80^{x}	<0.87
Dry-pack	8.10^{y}	8.21^{y}	<0.03	8.12^{xy}	8.02^{xy}	<0.50
Wet-pack	8.21^{z}	8.21^{y}	<0.97	7.95^{x}	8.21^{y}	<0.05
Soil	—	8.30^{y}	—	8.26^{y}	8.05^{xy}	<0.83
NH_x-N, mg/kg						
Loose	2,200^{x}	2,512^{y}	<0.35	2,574^{y}	2,276^{y}	<0.50
Dry-pack	2,190^{x}	2,194^{y}	<0.98	2,335^{y}	2,204^{y}	<0.58
Wet-pack	5,281^{y}	4,034^{z}	<0.01	3,956^{z}	3,779^{z}	<0.25
Soil	—	1,404^{x}	—	1,307^{x}	1,347^{x}	<0.96
Total N, g/kg						
Loose	28.8^{y}	28.4^{z}	<0.51	27.4^{z}	27.9^{z}	<0.34
Dry-pack	25.6^{x}	25.6^{yz}	<0.94	25.0^{yz}	25.9^{yz}	<0.53
Wet-pack	25.2^{x}	21.9^{y}	<0.01	22.1^{y}	24.0^{y}	<0.87
Soil	—	4.2^{x}	—	3.6^{x}	4.3^{x}	<0.92

$^{x–z}$Means within column and item with different superscripts differ ($P < 0.05$).

However, loose surface and dry-pack samples obtained on mounds had lower water content than samples taken away from the mound (Table 5). These differences might be expected because one of the purposes of the mound is to provide a drier pen surface for the cattle. As would be expected because of water spillage, the water content of loose, dry-pack, and wet-pack samples obtained near the water trough was greater ($P <$ 0.06 or greater) than that of samples taken more than 20 m from the water trough.

The pH of the loose and dry-pack layer samples obtained on the mound tended to be lower than samples taken off the mound (Table 5). The reason for this difference is not clear but could be related to greater nitrification or fermentation. The pH of the loose, dry-pack, and soil layers were not affected by proximity to a water trough; however, the pH of the wet-pack layer samples obtained near a water trough were lower than samples obtained away from the water trough.

The NH_x-N and total N concentrations in the loose and dry-pack layers were not significantly affected by mounding or proximity to a water

Table 6. Water, pH, and electrical conductivity (DM basis) of pen surface samples from fresh urine spots and nonurinated spots at feedyards A, B, and C

Item and layer	Urine spot	Nonurine spot	Pooled layer SEM	Urine spot effect, *P*-value
Water, %				
Loose	40.0^{z}	13.8^{x}	1.26	<0.01
Dry-pack	28.3^{y}	17.8^{x}	0.81	<0.01
Wet-pack	33.4^{z}	31.2^{y}	0.38	<0.74
Soil	12.9^{x}	11.5^{x}	0.19	<0.22
pH				
Loose	8.10	7.85	0.06	<0.01
Dry-pack	8.13	8.11	0.05	<0.37
Wet-pack	8.23	8.28	0.05	<0.39
Soil	8.15	8.17	0.05	<0.78
Electrical conductivity, S/m				
Loose	1.56^{y}	1.26^{y}	0.058	<0.02
Dry-pack	1.33^{y}	1.11^{y}	0.069	<0.10
Wet-pack	1.31^{y}	1.29^{y}	0.098	<0.49
Soil	0.47^{z}	0.46^{x}	0.078	<0.76

$^{x–z}$Means within column and item with different superscripts differ ($P < 0.05$).

trough (Table 5). However, the NH_x-N and total N concentrations of the wet-pack layer were significantly greater in samples obtained on the mound than in samples obtained away from the mound. This might represent an accumulation of manure N within the mound. Overall, NO_x-N concentrations of samples obtained on the mound were similar to samples taken away from the mound. Mielke et al. (1974) found very little NO_x-N under manure mounds, probably because conditions are favorable for denitrification when manure is mounded to several inches.

Urine Effects: Feedyards A, B, and C

Water, pH, and EC of urine spot samples obtained from feedyards A, B, and C are presented in Table 6. Concentrations of OM, P, and C in the pen surface were not affected by recent urine application (data not shown). As would be expected, the moisture content of loose and dry-pack layer samples obtained from fresh urine spots was significantly greater than that of matching nonurine spot samples. However, recent urine application did not significantly affect the moisture content of the wet-pack and soil layers, which is probably because the bulk density of the dry-pack layer could promote lateral flow and thereby reduce moisture movement into the wet-pack and soil layers (Mielke et al., 1974; Mielke and Mazurak, 1976). In addition, the loose surface layer adsorbs a considerable proportion of urine and thus limits the quantity of urine available to enter the dry-pack layer. Mielke et al. (1974) reported that the infiltration of water in a feedlot surface is controlled by the combined effects of the surface and interface layers. In addition, microorganisms in the manure produce organic gels and polysaccharides that can fill soil pores and limit water infiltration.

The pH of the loose surface layer samples obtained from urine spots were significantly greater than those for drier areas without recent urine deposition (Table 6). The greater pH of the urine spots is probably due to the rapid hydrolysis of urinary urea to NH_x-N and CO_2 on the pen surface (Ernst and Massey, 1960; Haynes and Williams, 1992; Cole et al., 2009). Urine did not affect the pH of the dry-pack, wet-pack, or soil layer, again suggesting that the dry-pack layer prevents significant infiltration of urine to the wet-pack and soil layers of the pen surface. Urinary urea normally constitutes at least 60% of the total urine N (Whitehead et al., 1989) and as much as 70% of N intake (Cole et al., 2005; Todd et al., 2006). The resulting conditions of high NH_x-N concentrations and high pH that accompany urea hydrolysis on the pen surface are favorable for rapid NH_3-N volatilization (Ernst and Massey, 1960; Whitehead and Raistrick, 1993; Cole et al., 2009), especially during the warmer seasons (Elliott et al., 1971; Todd et al., 2008).

The EC of the loose layer from urine spots was significantly greater than areas without urine (Table 6). Ruminant urine is a concentrated solution of urea, Na, K, Cl, and other elements (Gustafson, 2000); therefore, areas that have recent urine deposition would be expected to have a greater salt content. Urination did not significantly affect the EC of the dry-pack, wet-pack, or soil layer of the pen surface.

The NH_x-N, total N, C-to-N ratio, and N-to-P ratio of pen surface samples collected from fresh urine spots are presented in Table 7. The NH_x-N concentrations of the loose surface and dry-pack layers were significantly greater for the urine spots than the

Table 7. Ammonium + ammonia N (NH_x-N), total N, NH_x-N as a percentage of total N, C-to-N ratio, and N-to-P ratio (DM basis) of pen surface samples from fresh urine spots and nonurinated spots within the same pen at feedyards A, B, and C

Item and layer	Urine spot	Nonurine spot	Pooled layer SEM	Urine spot effect, *P*-value
NH_x-N, mg/kg				
Loose	6,755^z	2,381^z	215.7	<0.01
Dry-pack	3,479^y	2,263^z	127.3	<0.01
Wet-pack	3,618^y	3,845^y	178.5	<0.79
Soil	1,699^x	1,390^x	92.2	<0.15
Total N, g/kg				
Loose	36.2^y	29.8^y	1.01	<0.01
Dry-pack	29.9^y	26.0^y	0.83	<0.02
Wet-pack	26.9^y	26.9^y	0.74	<0.80
Soil	4.8^x	3.9^x	0.41	<0.39
NH_x-N:total N, %				
Loose	21.84^y	8.47^x	0.25	<0.01
Dry-pack	13.78^x	9.75^x	1.31	<0.04
Wet-pack	15.13^x	16.16^y	0.67	<0.79
Soil	43.24^z	43.20^z	1.62	<0.85
C:N ratio				
Loose	11.7^y	12.7^y	0.14	<0.01
Dry-pack	11.1^y	11.8^y	0.17	<0.03
Wet-pack	11.2^y	11.3^y	0.14	<0.73
Soil	7.2^x	7.9^x	0.28	<0.39
N:P ratio				
Loose	4.76^y	3.85^x	0.122	<0.01
Dry-pack	3.95^x	3.63^x	0.093	<0.08
Wet-pack	3.41^x	3.19^x	0.084	<0.24
Soil	5.83^z	5.79^y	0.260	<0.45

$^{x–z}$Means within column and item with different superscripts differ ($P < 0.05$).

Table 8. Electrical conductivity, total C, ammonium + ammonia N (NH_x-N), and NH_x-N as a percentage of total N (DM basis) of the pen surface samples from feedyards A, B, and C taken from pens in which cattle had been on feed for a short (<45 d), medium (45 to 100 d), or long (>100 d) period of time

Item and layer	Long	Medium	Short	Pooled layer SEM	Days on feed effect, P-value
Electrical conductivity, S/m					
Loose	1.41^y	1.21^y	0.80^y	0.16	<0.01
Dry-pack	1.36^y	1.40^y	1.02^y	0.20	<0.33
Wet-pack	1.52^y	1.32^y	0.90^y	0.33	<0.36
Soil	0.42^x	0.37^x	0.32^x	0.09	<0.08
C, g/kg					
Loose	352^y	345^y	338^y	2.8	<0.02
Dry-pack	299^y	298^y	284^y	5.1	<0.95
Wet-pack	277^y	269^y	259^y	7.7	<0.72
Soil	59^x	29^x	22^x	3.8	<0.03
NH_x-N, mg/kg					
Loose	2,470^y	2,140^y	1,600^y	82.2	<0.02
Dry-pack	3,110^y	2,610^y	1,790^y	96.2	<0.01
Wet-pack	4,210^z	3,650^z	3,360^z	159.2	<0.04
Soil	2,170^x	1,540^x	750^x	68.1	<0.03
NH_x-N:total N, %					
Loose	10.18	8.56	7.29	0.25	<0.01
Dry-pack	17.89	8.75	7.73	1.31	<0.03
Wet-pack	23.40	13.47	10.76	0.67	<0.01
Soil	56.39	35.86	40.53	1.62	<0.06

$^{x-z}$Means within column and item with different superscripts differ ($P < 0.05$).

areas without fresh urine. The lower NH_x-N concentrations on the nonurine areas are probably a result of the volatilization of NH_3-N formed by rapid hydrolysis of urinary urea (Bremner and Mulvaney, 1978; Whitehead et al., 1989; Whitehead and Raistrick, 1993). In pasture soil (Petersen et al., 2004) and on feedlot pen surfaces (Cole et al., 2009), urinary urea is almost completely hydrolyzed within 96 h of deposition, providing NH_x-N for other N transformations. Soil moisture content is an important factor in NH_3-N volatilization because of its role in urea dissolution and hydrolysis and in the diffusion of urea, ammonium, and nitrate. Ernst and Massey (1960) reported that rapid drying conditions encouraged NH_3-N volatilization. However, urea hydrolysis and NH_3-N volatilization are inhibited once the soil becomes dry (Ferguson and Kissel, 1986; Reynolds and Wolf, 1987; Miller and Berry, 2005).

The concentration of total N in the loose surface and dry-pack layers was significantly greater for the urine spots than for areas without urine. However, the total N concentration of the remaining 2 layers was not affected by urine application. The proportion of total N present as NH_x-N was also greater in the loose surface and dry-pack layers of urine spots than nonurine spots. In pastures, Petersen et al. (2004) noted that NH_x-N represented 80% of applied N 4 d after urine application.

The C-to-N ratio of the loose surface and dry-pack layers was significantly lower for the urine spots than for the spots without urine; however, the C-to-N ratio of the wet-pack and soil layers was not significantly affected by urine. The significant difference in the C-to-N ratio between the urine spots and spots without urine in the loose surface and dry-pack layers was most likely the result of the high N content of urine. The N-to-P ratio of the loose layers was greater on urine spots than on nonurinated spots, which also tended to be true in the dry-pack layer ($P < 0.08$). These differences would be expected because ammonia-N losses from urine spots would result in a decrease in the N-to-P ratio. Total N volatilization losses from a commercial feedyard, as measured by the change in the N-to-P ratio between diets and air-dried manure, are similar to ammonia-N emissions measured using several micrometeorological methods (Flesch et al., 2007; Todd et al., 2008).

There was no significant effect of urine on NO_x-N concentrations in the pen surface layers (data not shown). Urine spots are an environment that would be expected to stimulate nitrification. However, on pasture soils, nitrifying bacteria are apparently inhibited under urine spots because of combined inhibitory effects of high pH (>7.2), free NH_3-N (0.1 to 1.0 mg N/L), and osmotic stress (NaCl = 0.5 to 1% concentration), resulting in nitrite accumulation (Monaghan and Barraclough, 1992). However, the inhibition appears to be transient. Petersen et al. (2004) and Monaghan and Barraclough (1992) noted that little NO_x-N accumulated in pasture soils during the first 4 d after urine application. However, 5 to 14 d after urine application, NO_x-N accumulation represented 17 to 23% of applied urea-N. Although several studies have looked at the effects of urine application and other factors on N transformations in pastures, it is not clear if similar changes occur on feedlot pen surfaces (Woodbury et al., 2001). The physical, microbial, and chemical conditions of a feedlot pen surface differ from those of a pasture. First, because of greater stocking density, urine may be applied more frequently onto the surface of a feedlot pen than a pasture. In addition, the microbial communities may differ. In pastures, soil bacteria may predominate, whereas on a feedlot pen surface, soil bacteria may be supplanted by fecal bacteria that are more ammonium tolerant. Third, plant uptake of soil N and water might alter N transformations in pasture soils.

Effects of Days on Feed: Feedyards A, B, and C

The length of time cattle had been on feed did not significantly affect pen surface water concentration, pH, NO_x-N concentration, total N concentration, or C-to-N ratio (data not shown). The EC, C concentration, and NH_x-N concentration of the loose layer increased as the length of time on feed increased (Table 8). The NH_x-N concentrations of the dry-pack, wet-pack, and soil layers also increased with days on feed. The increase in EC, C, and NH_x-N of the layers with additional days on feed might be expected because there would be more time for fecal and urinary minerals to accumulate in the pen surface layers and dilute soil concentrations in the manure.

IMPLICATIONS

The pen surfaces of feedlots develop a distinctive chemical, microbial, and physical ecosystem. The chemical composition of the feedlot pen surface appears to be affected by factors such as layer (i.e., depth, manure and soil mixing, compaction), environmental conditions (i.e., season), location within the pen, manure management, and recentness of urine application. The density of the dry-pack and wet-pack layers may form a zone that reduces percolation below the pen surface. Conditions on the loose pen surface are conducive to rapid conversion of urinary urea to NH_x-N with subsequent loss of NH_3-N. The relatively high pH of the anaerobic layers may limit production of N_2O in favor of di-N gas. The differences in the chemical and physical properties of the layers in a feedlot pen may potentially affect the quantities of NH_3-N, nitrous oxide, and N_2 emitted to the atmosphere and the NO_x-N and P that may leach to groundwater.

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